

Pulsar Timing Arrays and their Applications

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Abstract. Millisecond pulsars are intrinsically very stable clocks and precise measurement of their observed pulse periods can be used to study a wide variety of astrophysical phenomena. In particular, observations of a large sample of millisecond pulsars at regular intervals, constituting a Pulsar Timing Array (PTA), can be used as a detector of low-frequency gravitational waves and to establish a standard of time independent of terrestrial atomic timescales. Three major timing array projects have been established: The European Pulsar Timing Array (EPTA), the North American pulsar timing array (NANOGrav) and the Parkes Pulsar Timing Array (PPTA). Results from the PPTA project are described in some detail and future prospects for PTA projects are discussed.

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INTRODUCTION

Pulsars and especially millisecond pulsars (MSPs) are remarkably stable celestial clocks. This great period stability opens up a wide range of potential applications. Pulsar timing analysis is based on the measurement of precise pulse times of arrival (ToAs) at the telescope. These ToAs are then transformed to the Solar-System barycentre which approximates an inertial frame. A model for the pulsar, including its position, proper motion, period and period derivatives and binary parameters (if appropriate) can be used to predict the pulse ToAs. The difference between the observed and predicted ToAs are known as *timing residuals*. These timing residuals contain information about errors in the model parameters and unmodelled phenomena affecting the observed pulse period and so are at the heart of all pulsar timing analyses; see Hobbs et al. [1] and Edwards et al. [2] for more details.

A pulsar timing array (PTA) consists of an array of pulsars, widely distributed on the celestial sphere, that are being timed with high precision and at frequent intervals over a long data span [3, 4, 5]. Such a PTA has the potential to detect low-frequency gravitational waves propagating in the Galaxy [6, 7], to improve our knowledge of Solar-System parameters [5] and to establish a pulsar-based standard of time that is independent of terrestrial atomic timescales [8]. Only MSPs have sufficiently narrow pulses (in time units) and sufficiently stable periodicities to be useful for PTA applications.

DETECTION OF GRAVITATIONAL WAVES

Gravitational waves (GWs), a prediction of Einstein's general theory of relativity, are fluctuations in spacetime generated by acceleration of massive objects which propagate

at the velocity of light. Possible astrophysical sources include energy-density fluctuations in the inflation era, oscillations of cosmic strings, binary supermassive black holes in the cores of distant galaxies and double-neutron-star binary systems. Although the famous Hulse-Taylor binary pulsar has given the first observational evidence for the existence of gravitational waves through its orbital decay [9, 10], gravitational waves have never been directly detected despite huge efforts over more than four decades. Current projects such as *LIGO* [11] and *Virgo* [12] utilise laser-interferometer systems that are sensitive to GWs with frequencies in the range 40 – 1000 Hz. The planned space gravitational-wave observatory *LISA* [13] has much longer interferometer arms and is sensitive to GWs in the frequency range 0.1 – 100 mHz. In contrast, PTA systems are most sensitive to signals with frequencies about $1/T$, where T is the data span of the timing observations. Typically, $T \sim 10$ yr, corresponding to frequencies of a few nHz.

In this nHz band, the strongest GW signal is expected to be a stochastic background from binary super-massive black holes in the cores of distant galaxies [14, 15, 16]. Detection of this expected signal requires high-quality timing observations of about 20 MSPs over a data span of at least five years with timing precisions of the order of 100 ns [17]. This level of timing precision can only be obtained for a few MSPs with present technology but fortunately the expected signal has a very “red” spectrum (stronger at low frequencies) and so the required sensitivity can be recovered by observing for longer data spans. Specifically, for the stochastic background from binary super-massive black holes, the expected signal may be represented by

$$h_c(f) = A(f/f_{1\text{yr}})^\alpha \quad (1)$$

where $h_c(f)$ is the characteristic GW strain at frequency f , A is the dimensionless amplitude of the GW background, $f_{1\text{yr}} = (1\text{yr})^{-1}$ and the spectral index $\alpha = -2/3$ [17]. This leads to a $T^{13/3}$ dependence for the amplitude of the signal in the timing residuals [18].

The absence of any unmodelled signal (apart from “white” receiver noise) in the timing residuals for one or more pulsars can be used to limit the strength of the GW background in the Galaxy. Currently, the best published limit, based on archival Arecibo data and Parkes timing data for seven pulsars [19], is $h_c(f_{1\text{yr}}) < 1.1 \times 10^{-14}$. This limit does not significantly constrain current models for super-massive black hole evolution and mergers in galaxies [14, 15, 16] but does limit some models for the equation of state of matter in the epoch of inflation [21] and the tension in cosmic strings [22].

The principal aim of PTAs is not just to limit the stochastic GW background in the Galaxy, but to *detect* it. This detection depends on the correlated modulation of timing residuals for different pulsars as a GW passes over the Earth. GW are quadrupolar in nature so that modulations are opposite in sign for pulsars which are 90° apart on the sky. For an isotropic stochastic GW background, the correlation between residuals in different pulsars depends only on the angular separation of the pulsars. For general relativity, the expected correlation is given by the “Hellings and Downs” curve [3] shown in Figure 1. For pulsars close together on the sky, the correlation is 0.5 rather than 1.0 because of the uncorrelated modulations due to GW passing over the pulsars. These modulations also result in the “self-noise” apparent in the scatter of points about the theoretical line; this noise is independent of ToA precisions and limits the sensitivity of

PTA experiments in strong-field situations [17, 18].

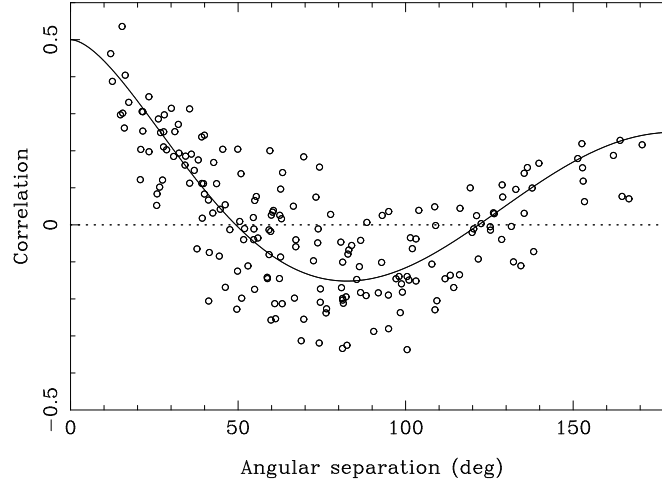


FIGURE 1. Correlation between timing residuals for pulsar pairs as a function of the angular separation of the two pulsars for an isotropic GW background in the Galaxy under general relativity [3]. The computations are based on the PPTA sample of 20 pulsars with a strong GW signal that dominates the timing residuals [18].

PULSAR TIMING ARRAYS AND GW APPLICATIONS

Currently there are about 35 MSPs that are both sufficiently strong and have sufficiently narrow pulse profile features to make them useful for PTA projects, i.e., to give ToA precisions of $\lesssim 1\mu\text{s}$ with observations times of an hour or so. Most of these are being regularly timed by one or more of the three major PTA projects: the European Pulsar Timing Array (EPTA), the North American pulsar timing array (NANOGrav) and the Parkes Pulsar Timing Array (PPTA). The EPTA combines data from the four large radio telescopes in Europe: at Nançay, Effelsberg, Westerbork and Jodrell Bank, with a fifth in Sardinia soon to be added [20]. NANOGrav uses data from the Arecibo radio telescope and the Green Bank Telescope [23]. The PPTA uses data from the Parkes 64-m radio telescope in Australia [24, 25, 26]. A collaboration exists between these three projects to form the International Pulsar Timing Array (IPTA) [27].

The PPTA project commenced in 2004 and regular timing of 20 MSPs commenced in 2005 March. The project is a collaboration principally between the groups at CSIRO Astronomy and Space Science (led by RNM and G. Hobbs) and Swinburne University of Technology (led by M. Bailes and W. van Straten) with major contributions from the University of Texas at Brownsville (F. A. Jenet) and the University of California at San Diego (W. A. Coles). Observations are made at intervals of 2 – 3 weeks in three bands: 10 cm (3100 MHz), 20 cm (1400 MHz) and 50 cm (700 MHz). The 10 cm and 50 cm observations use a dual-frequency coaxial receiver while the 20 cm observations are generally made using the centre beam of the Parkes 20-cm 13-beam receiver. A number of back-end systems have been used since the project commenced: the Wide-Band Correlator (maximum bandwidth 1024 MHz), a series of Parkes Digital Filterbanks PDFB1 (256 MHz) and PDFB2, 3 and 4 (1024 MHz), the Caltech-Parkes-

Swinburne Recorder CPSR2 (2×64 MHz) and the ATNF-Parkes-Swinburne Recorder APSR (1024 MHz). CPSR2 and APSR provide coherent dedispersion whereas the other systems give up to 2048 frequency channels for off-line dedispersion.

Table 1 lists the 20 MSPs observed as part of the PPTA project. The timing results are from 2.3 – 4.0 years of data recorded with PDFB2 and PDFB4. Except for PSR J1045–4509 the data are uncorrected for DM variations. In most cases, the observation time per ToA is 64 min. Rms timing residuals after fitting for the pulsar position, pulse frequency, its first time-derivative and the Keplerian binary parameters (if applicable) and the band at which they were obtained are listed. Most of the pulsars have rms timing residuals of less than $1\mu\text{s}$ and four are less than 200 ns. We are therefore approaching the level of timing precision needed for detection of the expected GW signal in the Galaxy. Some improvement in these results can be expected with improved calibration and signal processing procedures.

TABLE 1. PPTA pulsars and their timing residuals

PSRJ	Pulse Period (ms)	DM (cm^{-3} pc)	Orbital Period (d)	Band	RMS Residual (μs)
J0437–4715	5.757	2.65	5.74	10 cm	0.055
J0613–0200	3.062	38.78	1.20	20 cm	0.72
J0711–6830	5.491	18.41	–	20 cm	0.68
J1022+1001	16.453	10.25	7.81	10 cm	1.39
J1024–0719	5.162	6.49	–	20 cm	0.84
J1045–4509	7.474	58.15	4.08	20 cm	2.60
J1600–3053	3.598	52.19	14.34	20 cm	0.49
J1603–7202	14.842	38.05	6.31	20 cm	0.46
J1643–1224	4.622	62.41	147.02	20 cm	0.80
J1713+0747	4.570	15.99	67.83	10 cm	0.23
J1730–2304	8.123	9.61	–	20 cm	1.46
J1732–5049	5.313	56.84	5.26	20 cm	2.43
J1744–1134	4.075	3.14	–	20 cm	0.18
J1824–2452	3.054	119.86	–	20 cm	1.66
J1857+0943	5.362	13.31	12.33	20 cm	0.62
J1909–3744	2.947	10.39	1.53	10 cm	0.095
J1939+2134	1.558	71.04	–	10 cm	0.18
J2124–3358	4.931	4.62	–	20 cm	1.62
J2129–5721	3.726	31.85	6.63	20 cm	1.35
J2145–0750	16.052	9.00	6.84	20 cm	0.65

It is clear that longer data sets are needed to achieve the sensitivity required to detect the GW background. Verbiest et al. [28] has shown that most of the PPTA pulsars have sufficiently stable periodicities over a 10-year data span. However, this analysis included arbitrary phase offsets between data obtained with different instruments which absorbed some of the low-frequency power in the residual spectrum. Figure 2 shows timing residuals for PSR J0437–4715 over a nearly 14-year data span. Offsets between the different instruments were measured using local fits and then held fixed in the final fit which included just the first period time derivative. These residuals obviously have red spectrum, the origin of which is currently unknown.

If such red noise is shown to be intrinsic to the pulsar and present in most MSPs, it will have to be properly taken into account in searches for GW and other analyses,

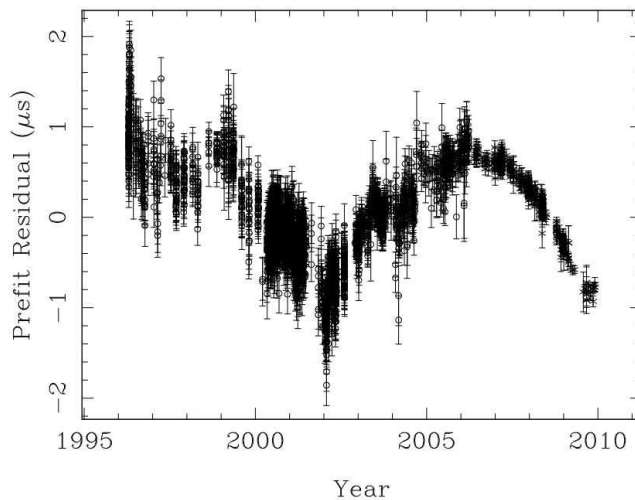


FIGURE 2. Timing residuals for PSR J0437–4715 for a 14-year data span formed by combining the Verbiest et al. [29] data with more recent 10 cm PPTA data (from 2006.5).

for example, by using the Cholesky technique [30]. It will not prevent detection of the GW signal since, like the GW self-noise, it is uncorrelated between different pulsars; it will however add noise to the correlations and make the detection more difficult. The most effective way to overcome such limitations is to increase the number of pulsars in the PTA sample; this is a principal motivation for the IPTA collaboration. In the future, the Square Kilometre Array (SKA) [31] will have enough sensitivity to obtain useful data from a much larger sample of pulsars. This should allow not only the detection of GW signals [16, 32] but also the study of the GW sources in some detail. It will also allow detailed investigations of the properties of the GW themselves, perhaps revealing non-Einsteinian behaviour [33].

While the stochastic background is predicted to be the strongest and most easily detectable GW signal for PTAs, the SKA is likely to provide sufficient sensitivity to detect and study individual sources of GW [34, 35]. Figure 3 gives a realistic PTA sensitivity curve applied to detection of individual GW sources in the Virgo cluster [35], showing that a binary black-hole system with component masses of a few $10^9 M_\odot$ and orbital period of less than about 5 years would be detectable with present data sets. Anholm et al. [36] showed that a sufficiently strong GW source in the Southern Hemisphere can be localised to a few degrees using the PPTA pulsar sample. A more uniform distribution of pulsars on the sky, provided for example by the IPTA, would extend this resolution to the Northern Hemisphere.

OTHER PTA APPLICATIONS

PTA data sets have many applications besides the search for GWs. For example, essentially all PTA data are recorded with full polarisation information and hence can be used to study polarisation properties of MSPs. This in turn has applications to studies of the

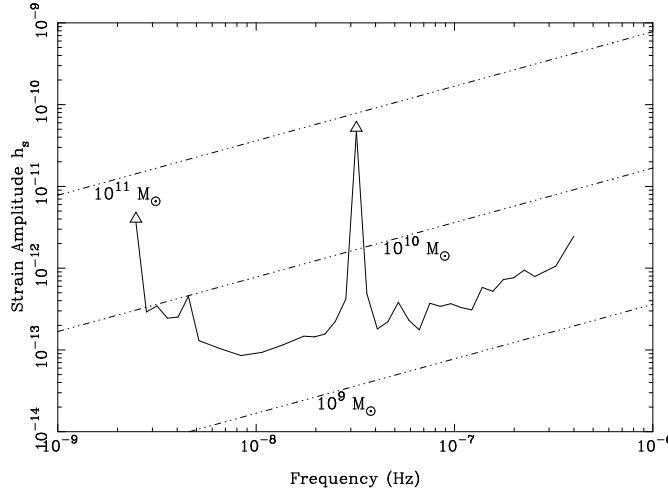


FIGURE 3. Sensitivity of a PTA based on the Verbiest et al. [28] data set for detection of a source of GW in the Virgo cluster including all effects of the timing analysis [35]. The dot-dashed lines show the expected signal for equal-mass binary black-hole systems in the cluster.

pulse emission process in pulsars and to studies of the Galactic magnetic field. Timing data for individual MSPs can be used to study their astrometric and binary properties, including proper motions, parallaxes and studies of binary evolution and neutron-star masses. Multi-frequency data sets can be used to investigate interstellar dispersion and scattering, giving information on the small-scale fluctuations in the interstellar medium [37].

Pulsar timing analyses are dependent on a Solar-System ephemeris to transfer observed ToAs to the Solar-System barycentre. Commonly used ephemerides such as those from the Jet Propulsion Laboratory (e.g., [38]) are based on fits to large data sets including optical astrometry and radar ranging of the planets. PTA observations give an independent method of estimating the mass of the Solar-System planetary systems. An error in an assumed planetary mass will induce a signal in pulsar timing residuals at the orbital period of the planet. This signal has a spatial dipolar signature as opposed to the quadrupolar signature of GW and hence can be separated in PTA data sets. Champion et al. [39] have used PPTA data together with archival Arecibo data to measure the masses of the Solar-System planetary systems with an uncertainty of order $10^{-10} M_{\odot}$. For the Jupiter system, this is a factor of four better than the best result published in the open literature, but still a factor of about 20 worse than the value obtained from observations of the *Galileo* spacecraft. Longer and more complete PTA data sets have the potential to give us the most precise masses for some planetary systems.

PTA data sets also can be used to establish a standard of time which independent of terrestrial atomic timescales [8]. Fluctuations in the atomic timescale introduce systematic residual fluctuations which have a monopole signature, that is, they are the same for all pulsars regardless of their position on the sky. Figure 4 shows the results from an analysis of PPTA data by Hobbs et al. [40]. While there is good agreement between TT(TAI) and the pulsar timescale TT(PSR) over the last five years or so, these results indicate that TT(TAI) was running fast around 1997. The retroactively revised atomic

timescale TT(BIPM2010) shows similar deviation at this time, confirming the accuracy of both the pulsar results and the atomic timescale revision.

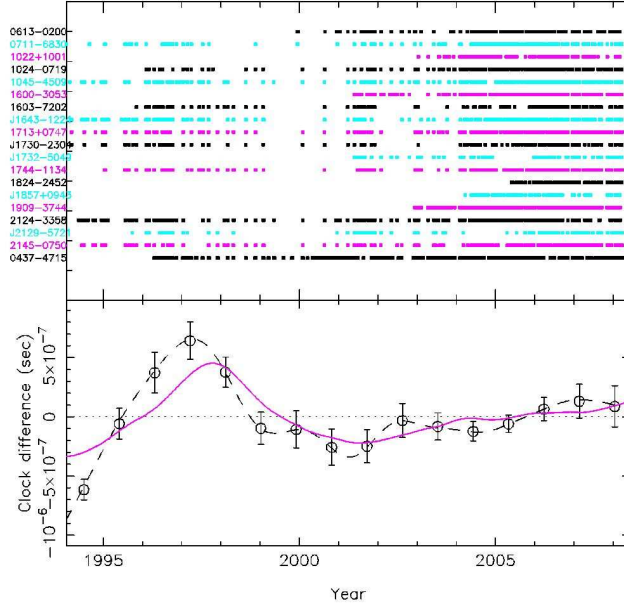


FIGURE 4. A pulsar timescale based on the extended PPTA data set [40]. The upper panel shows the data sampling for the pulsars used in the analysis. In the lower panel the dashed line is the derived pulsar timescale relative to TT(TAI) (in the sense $TT(TAI) - TT(PSR)$) and the solid line is $TT(TAI) - TT(BIPM2010)$ with a quadratic polynomial removed.

CONCLUSIONS

The realisation of Pulsar Timing Arrays is an exciting new development in pulsar astrophysics. PTA data sets have many applications including the detection of low-frequency gravitational waves and the establishment of a pulsar-based standard of time. Combining of existing and future data sets to form an International Pulsar Timing Array will give improved results in all applications. Looking further into the future, the greatly increased sensitivity provided by the proposed Square Kilometer Array will make possible detailed studies of phenomena presently near or below the level of significant detection.

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